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THERMAL AND FAST NEUTRON EFFECTS ON DOSIMETER FILMS

by

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FOREWORD

In order to accurately measure the initial gamma radiation from atomic detonations, the effects of neutrons on the gamma detectors must be evaluated. Film dosimeters were the major gamma detectors used at weapons tests. Since film can be affected directly by neutron interaction and indirectly by the production of capture gamma in the detectors' environment, a series of three reports has been written to cover the field.

This report describes experiments to determine the direct effect of thermal and fast neutrons on dosimeter films. This work was authorized under DASA Project Number 06.07, Army Task Number 4N12-10-007-04, Neutron Effects on Gamma Detectors. The work on which this report is based was begun in July 1960 and completed in May 1961.

Acknowledgments

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The author expresses his appreciation to Mr. Ross Larrick of the U. S. Army Signal Research and Development Laboratory for the calibration and processing of the large number of irradiated films. The contributions of Mr. Ronald Sasse and SP4s Ralph Benck, Leonard Dworken, and James Harris, of the Nuclear Chemistry Division of Nuclear Defense Laboratory, to various phases of this work are gratefully acknowledged.

Disposition

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DIGEST

Film dosimeters used at weapons tests to measure initial gamma radiation are sensitive to neutrons and to the gamma radiation produced by the interaction of neutrons with the environment of the film. The purpose of this work was to experimentally evaluate the direct effect of neutrons on film dosimeters.

Eight film types encased in NBS holders and covering a range of 0.3 to 50,000 r were exposed to neutron radiation at the North Thermal Column of the Los Alamos Water Boiler Reactor and the Los Alamos Cockcroft-Walton and Van de Graaff Accelerators. The lithium extrapolation method was used to evaluate the thermal-neutron sensitivity of the films. This method is explained and refinements are reported.

The thermal-neutron and fast-neutron sensitivities of the eight films that have been determined by this experiment can be utilized to correct film data obtained at nuclear weapons tests.

Further experimental work with fast neutrons is needed to increase the statistical accuracy of our results as well as to obtain fast-neutron sensitivities of the very high-range films, 548 and 649. Two points seem evident concerning the fast-neutron sensitivity of film. They are: (1) the sensitivity of the films increases with increasing neutron energy from 1 to 14 Mev, and (2) the ratio of the sensitivities of the films is roughly equal to the reciprocal of the ratio of their grain sizes.

In order to obtain meaningful data from neutron experiments conducted in a reactor thermal column, corrections must be made for the neutron sink effect of the object being irradiated. The lithium-extrapolation method for obtaining these correction factors has been refined and revised so that the method may be used with confidence.

MILITARY APPLICATION

This report discusses one of the methods used to correct initial gamma measurements made in the field. A field commander must know the initial gamma dose from a particular type weapon at various distances so that he may position his troops to the greatest advantage without exposing them to significant gamma doses.

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THERMAL AND FAST NEUTRON EFFECTS ON DOSIMETER FILMS

I. INTRODUCTION.

Initial gamma radiation has been measured at various distances from most of our test detonations of nuclear weapons. Unfortunately, the measuring devices used are also somewhat sensitive to neutron radiation. In addition, the shielding necessary to protect these devices from blast and thermal radiation produces secondary gamma rays when exposed to neutrons. Therefore, the gamma measurements are more or less in error, depending on the magnitude of the neutron radiation. The objective of this investigation was to determine the direct effect of thermal and fast neutrons on photographic film dosimeters. Film dosimeters, usually encased in the National Bureau of Standards holders, were the principal initial gamma detectors utilized at the test detonations.

This report is the first of four reports dealing with the neutron effects on film dosimeters. While this report is concerned with the direct interaction of neutrons with film and holder, the next two reports will be concerned with the neutron effects upon the environment of the film used in the field, namely, the soil and blast and thermal shields. Since neutron radiation was measured at the test detonations, the results obtained from these reports will be used to correct the initial gamma data for the neutron effects and will be recorded in the fourth and final report in this series.

Relatively little has been published on the neutron sensitivity of commercial photographic film. Experimental studies by Hendrickson, et al.[1], at a weapons test and by York[2] at the Los Alamos Pulse Reactor (Godiva), were handicapped by a poorly known gamma component and complicated geometry. Tochilin, et al.[3], attempted to determine the extent of the difficulty introduced by fast neutrons by means of the University of California's 60-in. cyclotron. Tochilin was also handicapped by complicated geometry and poorly known gamma-ray background.

Mercer and Golden[4] mathematically and experimentally derived a formula for calculating the thermal-neutron sensitivity of a number of films. Their experimental work suffered from the same faults as the previously mentioned experiments. In their mathematical treatment they neglected the activation of the halogen, mainly bromine, in the silver halide. In addition, their work was based on an electron calibration instead of an X-ray calibration, and their formula applies only to bare film and to one of the eight types in which there is greatest interest.

Ehrlich[5] recently published experimental results on the effects of thermal and 3-Mev neutrons on three film types. She used the thermal columns at Los Alamos Scientific Laboratory (LASL) and Oak Ridge National Laboratory (ORNL) as the sources for thermal neutrons and the NBS 2-Mev Van de Graaff as the source for the 3-Mev neutrons.

II. THEORY AND APPROACH.

A. Neutron Interaction With Film.

Thermal neutrons are captured mainly in the bromine and in the silver of the film. The radioactive nuclides produced in this process have rather complicated decay schemes, involving a number of high and low-energy gamma rays, as well as beta radiation, and their half lives vary from a few seconds to several hundred days. Besides the thermal neutron capture reactions, there are also (n,p) reactions in carbon and particularly in the nitrogen of the gelatin base. This effect can be neglected since film exposure due to the protons from nuclear reactions induced by thermal neutrons is small compared to that due to decay produced from the thermal-neutron activations.

The fast neutrons interact with the film and holder mainly by elastic and inelastic scattering on hydrogen and carbon to produce proton recoils and gamma rays. Elastic scattering is the predominant interaction for neutrons with energies less than 8 Mev.

Ehrlich[5] states that preliminary investigations indicate that the predominant portion of the photographic effect is due to proton recoils from elastic scattering of fast neutrons on the hydrogen of the emulsion, of the film base, and of surrounding materials, such as the paper of the film packet and the plastic of the film holder. Gelatine, film base, paper, and plastic have somewhat similar hydrogen densities. Since the range of the recoiling protons is less than the combined thickness of these substances, the film exposure took place under conditions not far from proton equilibrium.

B. Thermal Neutron Approach.

A useful source of pure thermal neutrons is not readily available. Thermal neutrons are always accompanied by gamma rays. Since film is very sensitive to gamma rays, it was desirable that the sources of thermal neutrons be accompanied only by a small and well-known gamma component. The source that best met the requirements was the North Thermal Column at the Los Alamos Water Boiler Reactor. Since the thermal column is small in size and the detector has a finite size, a correction had to be made for the neutron sink effect of the detector.

Thermal neutrons have very low energies, of the order of 0.025 ev, and thus they act like a gas with the same random-type motion.

A detector of any size will disturb this motion not only by being there but also by absorbing the neutrons. By absorbing the neutrons, the flux is lowered; therefore, the readings are always lower than the true values depending on the size and cross section of the detector. The perfect detector would be one which was infinitely small. One of the better detectors is a gold foil of 1/2 in. diameter and 10 mils thick. Corrections for the sink effect of even this small size detector must be made.

The method for obtaining this neutron sink correction is called lithium extrapolation. The efficiency of the lithium in absorbing thermal neutrons is so much greater than the film and holder that the sink, due to the film and holder, is made negligible by comparison.

Lithium is a 1/v absorber in which thermal neutrons are absorbed by the following reactions:

$Li^6(n,)H^3$, cross section - 900 barns, no gammas.
$Li^7(n,)Li^8$, cross section - 0.033 barns, total gama-ray energy 1.98 Mev.

Although neutron capture in Li^7 produces a high-energy gamma photon and Li^7 is more abundant than Li^6 (92.5% to 7.5%) in natural lithium, the large difference in cross sections results in only one capture in 2,000 taking place in Li^7. Consequently, relatively few capture gamma rays are produced and can be neglected.

The following is a step-by-step procedure for using the lithium-extrapolation method:

1. Obtain film response to the mixed gamma ray and thermal neutron field at various thicknesses of lithium.

2. Subtract the known gamma background from the film response at the different lithium thicknesses. This should then give the film response to thermal neutrons in equivalent roentgens.

3. Divide the experimentally obtained thermal-neutron flux in neutrons per square centimeter at each lithium thickness by the thermal neutron response of the film in roentgens.

4. Plot these values of thermal neutrons per square centimeter per roentgen versus lithium thickness and extrapolate the line back to 0 lithium. The value at 0 lithium is the true thermal neutron response of the film as compared to the film calibration source, usually Co^{60} radiation.

C. Fast Neutron Approach.

High fluxes of fast neutrons are available from many reactors. These fast neutrons, however, are usually accompanied by a large gamma component and a smaller thermal-neutron component that increases with distance from the source. Often the fast neutron spectrum is unknown. Since the sensitivity of film to fast neutrons varies with energy, knowledge of the neutron spectrum of the source is necessary.

Nearly monoenergetic neutrons are available from accelerators and these neutrons are not initially contaminated with other radiation. The fluxes obtainable are usually orders of magnitude lower than reactor fluxes. The good points of an accelerator irradiation, however, outweighed its bad points, and the LASL accelerators were available for our use at the time our thermal-neutron exposures were made. Thus, the 7-Mev Van de Graaff and the Cockcroft-Walton accelerators at Los Alamos were used for this experiment.

Even though accelerator neutrons do not have a gamma component when they are formed, by the time the neutrons reach the sample (film and holder) there is a small gamma background that has to be evaluated. This gamma background is produced by neutron interaction with the target material, the sample supports, and other objects near the neutron beam. An uncluttered sample area is essential for accurate work.

III. EXPERIMENTAL.

A. Films.

Table 1 presents pertinent film data. Some of the films are duplicates in their range and in some other properties. This is so because half the films (508, 510, 1290, and 649) are replacements for the older types. Film types 502, 510, 606 are marketed together in a single dental X-ray type packet to cover a range of 0.3 to 2500 r. The 508, 510, and 1290 films are also marketed in a similar packet. The 548-0 and 649 films are obtained singly in a packet. These particular films were chosen to be evaluated because they were the main types used at weapons tests.

B. National Bureau of Standards Holder.[6]

Unshielded film is energy dependent and has a sharp increase in sensitivity to gamma rays of energy less than 0.1 Mev. The NBS holder was designed to minimize this energy dependence by absorbing energies below 0.1 Mev. The holder plus film is used to measure dosages from 0.3 to 50,000 r in the energy range of 0.1 to 10 Mev. The holder consists of a bakelite container, density of 1.4 g/cc, 8.25 mm thick to provide electronic equilibrium (electrons generated in the film but escaping before detection are balanced by the electrons escaping from the bakelite into the film). The bakelite is covered with

TABLE 1

FILM INFORMATION

Film type	Silver halide thickness	Gelatine thickness	Base thickness	Grain size of undeveloped silver halide	Recommended range	Manufacturer
	g/sq cm	mg/sq dm	mg/sq dm	μ	r	
502	0.00206	262	2.750 *	1.0-1.5	0.3-10	Dupont
510	0.00350	446	2.470*	0.2-0.5	10-35	Dupont
606	0.00072	70.7	1.750*	0.5	35-2500	Dupont
508	0.00210	232	2.750*	2.0-2.5	0.3-10	Dupont
510	0.00350	446	2.470**	0.2-0.5	10-35	Dupont
1290	0.00052	200	2.750*	0.5	35-2500	Dupont
548-0					2500-50,000	Eastman-Kodak
649	0.00094	150		0.03-0.05	2500-50,000	Eastman-Kodak

*Cellulose acetate base.

**Polyester base.

1.07 mm of tin, which is in turn covered by 0.3 mm of lead. The tin and lead provide the energy independence in the range 0.1 to 10 Mev. The NBS holder was used extensively at weapons tests.

C. Experimental Setup.

1. Thermal Neutrons.

The essential features of the Water Boiler Reactor and the North Thermal Column[7] are shown in figure 1. The thermal column was constructed specifically to provide a large flux of thermal neutrons and a maximum neutron to gamma-ray ratio. The gamma-ray flux was lowered by blocking the gamma rays from the core with bismuth and by using boron instead of cadmium shielding around the column.

Thermal-neutron fluxes were measured with gold and cadmium-covered gold foils using the cadmium difference technique. This technique also provides information on the cadmium ratio, which is the ratio of the population of thermal neutrons to neutrons of energy above 0.3 ev.

The films encased in an NBS holder surrounded by the concentric lithium cylinders were irradiated inside the graphite cavity. Each lithium cylinder was 1/8 in. thick and the outer lithium cylinder was 5-1/2 in. in diameter and 13-1/2 in. long. Each cylinder was closed at the end closest to the reactor sphere with a circular piece of lithium also 1/8 in. thick.

2. Fast Neutrons.

The 14.1-Mev neutrons were obtained from the Los Alamos Cockcroft-Walton accelerator by a D-T reaction, $H^3(d,n)He^4$. The film and holders were placed in the 90° plane and 10 cm from the target. The target was a flat piece of zirconium metal saturated with tritium. The number of neutrons was determined by an alpha counter placed above the target measuring directly the alpha particles produced in 1 to 1 coincidence with the neutrons by the D-T reaction.

Neutron energies of 1.00 ±0.33, 2.00 ±0.25, 4.00 ±0.17, 6.0 ±0.5, and 8.0 ±0.4 Mev were obtained at the Los Alamos 7-Mev Van de Graaff by D-D and p-T reactions. The film and holder were placed 10 cm from the target in the forward direction. The target consisted of a brass cylinder filled with either deuterium or tritium gas. The neutron-emitting end was closed with a thin gold foil and the other end was closed with two thin molybdenum foils. The neutrons were monitored by a fission detector. The fission monitor consisted of a small geometry ionization chamber used to detect fission fragments from a 3 mg U^{238} foil. The neutron flux can be measured with an uncertainty of only 5%.

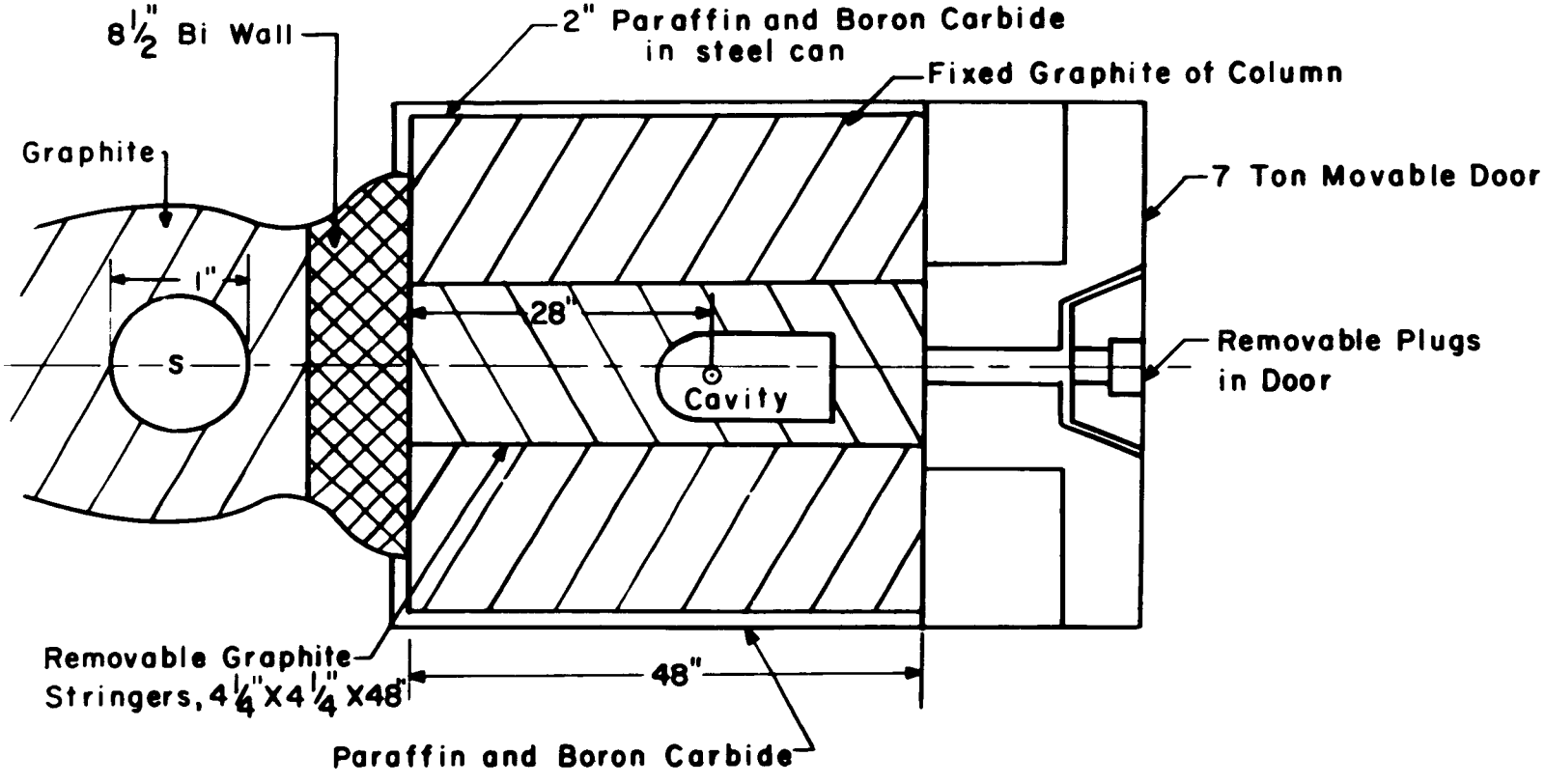

FIGURE 1

SCHEMATIC DRAWING OF GEOMETRY USED AT THE LOS ALAMOS WATER BOILER

D. Calibration.

Film is sensitive to environment and manufacture. Therefore, for accuracy, each batch of film must be calibrated at the same time experimental exposures are made. Unexposed control film should be set aside to provide background data. The control, calibration, and experimental film should be processed together.

The films were all calibrated and processed at U. S. Army Signal Research and Development Laboratory.

E. Processing of Film.

The method of processing the film is extremely critical. Time, bath temperature, and type of developer all seriously affect accuracy and reproducibility of the film. In fact, it is impossible to determine the neutron effect on film when the film is processed in a weak developer such as Kodak D-76[5]. All the films were processed for 5 min. at 20.80° ± 0.02° C with Kodak liquid X-ray developer.

IV. DISCUSSION OF EXPERIMENTAL TECHNIQUES.

A. Thermal-Neutron Flux.

The thermal-neutron flux in the thermal column was experimentally determined by using gold and cadmium-covered gold foils from 0 to 5 lithium thicknesses. The curve of thermal-neutron flux versus lithium is presented in figure 2. There were 12 lithium cylinders available but we used only the 5 largest cylinders. In working from 5 to 1 lithium we removed the concentric lithium cylinders from the inside, thus the largest lithium cylinder was used for the measurement at 1 lithium.

Suppose that the lithium cylinders were removed from the outside instead of removing them from the inside. Would the same thermal-neutron-flux curve be obtained? Let us consider this situation for the full 12 lithium cylinders.

A general formula for the absorption of thermal neutrons has been worked out by Graves and Roach[8] who found that the number of thermal neutrons absorbed was a function of the thickness and surface area of the absorber, among other factors. The surface area of the largest lithium cylinder is over 250 sq in., while its thickness is only 1/8 in. The smallest cylinder has a surface area of about 50 sq in.

As the lithium cylinders are removed from the inside from 12 to 1 lithium, the thickness changes by a constant amount (1/8 in.), while the surface area (which is the surface area of the outer or largest cylinder) remains constant. The thermal-neutron flux of the

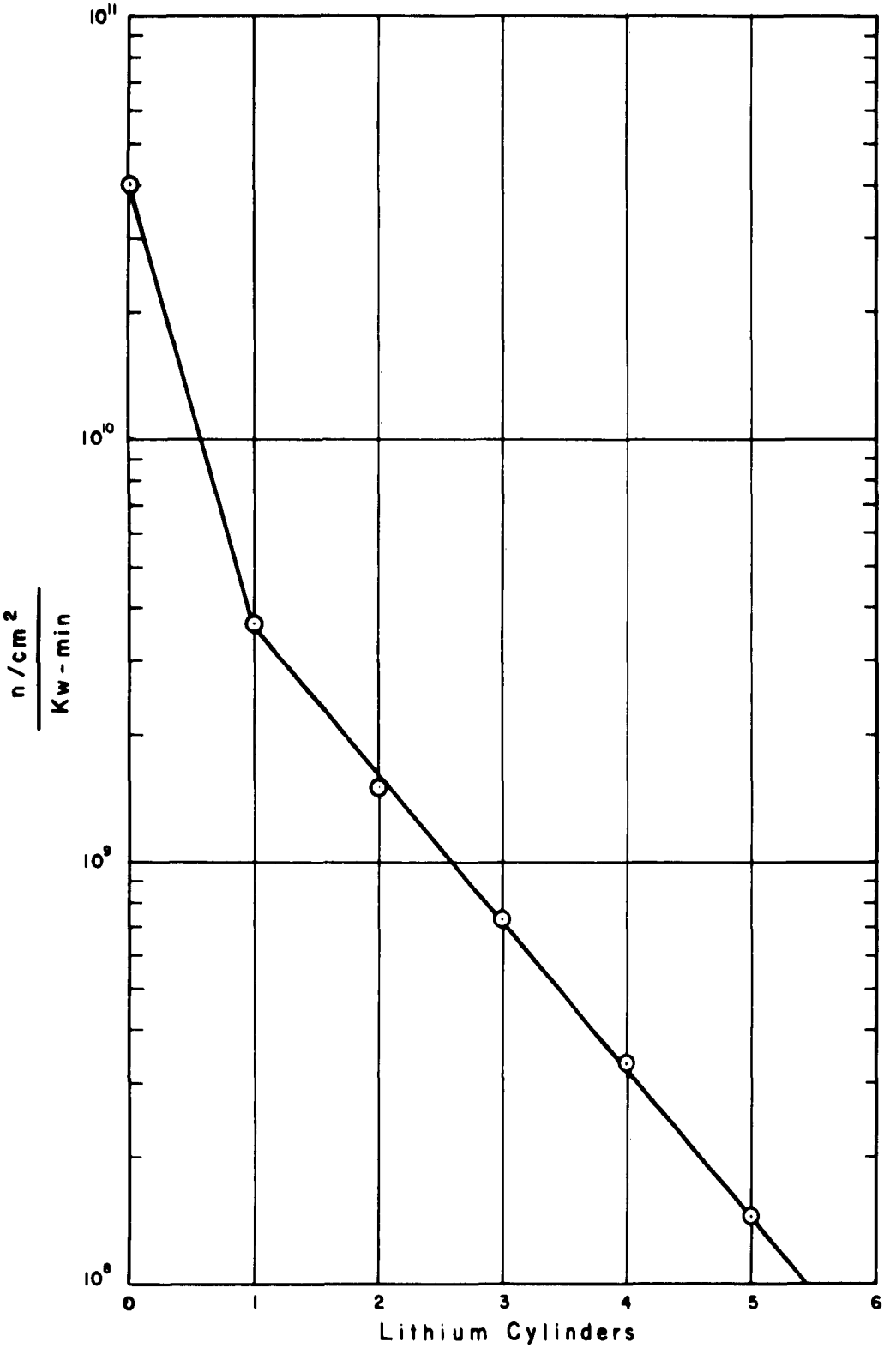

FIGURE 2

THERMAL-NEUTRON FLUX VERSUS NUMBER OF LITHIUM CYLINDERS

NDL curve, shown in figure 2, from 5 lithium to 1 lithium changes by a constant factor of 2.2 for each additional lithium cylinder. The curve should change by this same factor from 5 to 12 lithium. When the largest or outermost cylinder is removed, however, the thickness is again changed by 1/8 in., but the surface area is changed from 250 sq in. to 0. This tremendous change in surface area is represented in the curve by the large drop in flux from 0 to 1 lithium. This drop is the neutron sink effect of the lithium.

On the other hand, removing the lithium cylinders from the outside, the smallest or innermost cylinder is the last to be removed. The surface area of this cylinder is only 50 sq in. Thus, the change from 1 to 0 lithium using the outside-removal method produces a much smaller surface area change than the method we used. A graph of neutron flux versus number of lithium cylinders using the outside-removal method should show a smaller sink effect from 0 to 1 lithium than the inside-removal method. Since the difference in surface areas between the last cylinder in each method is a factor of 5 (250 to 50), the neutron flux at 1 lithium for the outside-removal method should be about a factor of 5 higher than the flux obtained from the inside-removal method.

Using the outside-removal method from 12 lithium to 1 lithium changes not only the thickness of the lithium by a constant amount but also changes the surface area by a nonconstant amount. Therefore, the change in neutron flux between 1 and 12 lithium for the outside-removal method should be greater than for the inside-removal method where only the thickness changes. Thus, the curve for the outside-removal method should show a steeper slope from 1 to 12 lithium than the curve for the inside-removal method.

Another factor to consider is that the thermal flux should be the same for both methods when all the lithium cylinders are used. The two curves should intersect at 12 lithium. The intersection of the curves at 12 lithium will occur only if detectors with the same response to the radiation in the thermal column are used. Bare gold and indium foils are sensitive to epicadmium neutrons. Curves using these detectors will be much different from curves obtained using cadmium-covered gold.

Since different curves for thermal-neutron flux will be obtained depending upon the method of removal of lithium and the type of detector used, great care must be exercised in using other investigator's data. Experimenters using the lithium-extrapolation method would do well to determine the thermal-neutron flux for themselves.

B. Gamma Flux.

The gamma flux will be affected by the lithium in the same manner as the thermal-neutron flux. This statement seems rather strange since 10 lithium cylinders will reduce an incident 4.5-Mev (average gamma energy in thermal column) gamma flux by only 5%. The explanation lies in where and how the gamma rays are produced.

Extensive investigations by Los Alamos personnel proved that no gamma rays produced in the reactor sphere reached the cavity.[9] The only source of gamma rays is from the interaction (n,γ) of thermal neutrons with the graphite of the reactor. Therefore, anything that affects the thermal flux will similarly affect the gamma flux. With respect to the empty cavity, the neutrons diffusing through the thermal column may be divided into two categories:

1. Neutrons that enter the cavity one or more times before being captured.

2. Neutrons that never enter the cavity.

These are the cavity and noncavity neutrons.

Similarly the total population of the gamma photons in the thermal column may be divided into two groups, cavity and noncavity photons. We are interested only in the cavity photons. This class may be further divided into:

1. Photons created by capture of cavity neutrons.

2. Photons created by capture of noncavity neutrons.

The usefulness of these terms lies in the fact that cavity neutrons and hence cavity neutron gamma rays are subject to capture in the lithium cylinders. On the other hand the flux of noncavity neutron gamma rays entering the cavity is not influenced by the lithium. Thus, the gamma curve should also be affected by the method of removing the lithium cylinders.

Our gamma curve is shown in figure 3. The curve was obtained by monitoring the gamma component with glass dosimeters and from information concerning the ratio of cavity gamma flux due to cavity neutrons to cavity gamma flux due to noncavity neutrons.[9]

C. Epicadmium Effect.

The cadmium ratio (ratio of thermal neutrons to epicadmium neutrons) of the thermal column had been assumed to be 700 to 1. Therefore, we ignored the epicadmium contribution in our calculations.

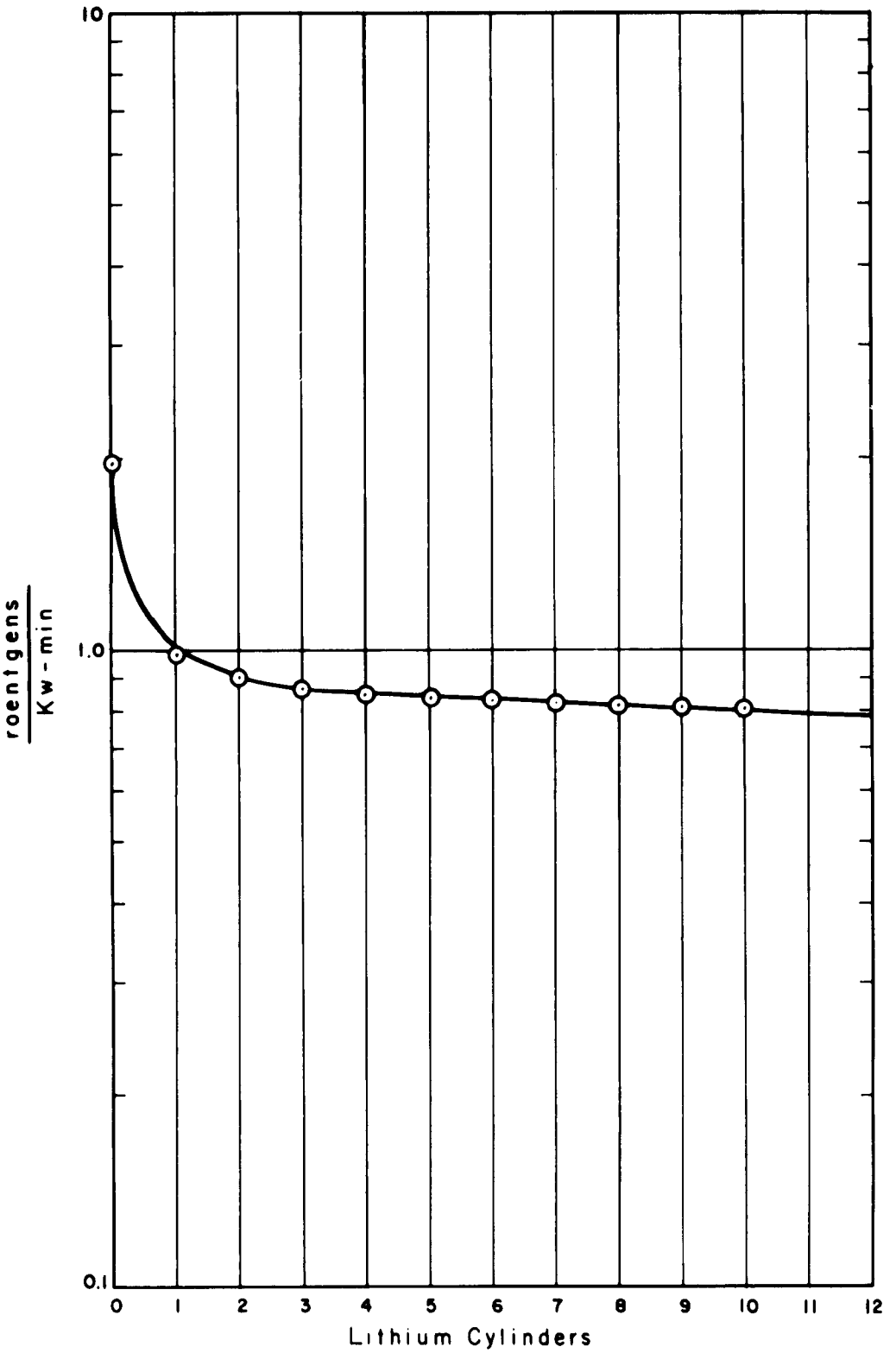

FIGURE 3

GAMMA FLUX VERSUS TOTAL NUMBER OF LITHIUM CYLINDERS

In consequence, instead of obtaining a nearly horizontal straight line for thermal-neutron sensitivity versus lithium, we obtained curves that increased in thermal sensitivity from 0 to 2 lithium and decreased from 2 to 5 or 6 lithium. The two types of curves are illustrated in figure 4.

When the gamma flux curve is subtracted from the experimental film curve, the resulting curve should have a shape similar to the thermal-neutron-flux curve if only thermal neutrons are affecting the film. We obtained curves, as illustrated in figure 5, where the curve begins to flatten at the larger lithium thicknesses. It was obvious that something else, which was only slightly affected by the lithium, was operating on the film. The logical choice was the epicadmium neutrons.

The cadmium ratio versus number of lithium cylinders was obtained from the gold and cadmium-covered gold foil data, and is shown in figure 6. The shape of this curve is similar to the thermal-neutron-flux curve; however, the slope of the cadmium-ratio curve is less than the slope of the thermal-neutron curve. The cadmium ratio rapidly decreases with increasing number of lithium cylinders so that at 7 lithium there is a greater number of epicadmium neutrons than thermal neutrons. Thus, the experimental film data minus the gamma component when plotted versus lithium should flatten in the vicinity of 7 lithium as was illustrated in figure 5. Extrapolating the flat portion of this curve back to 0 lithium and subtracting this extrapolation from the curve should eliminate the epicadmium contribution.

By eliminating the epicadmium effect, we were enabled to obtain thermal-neutron-sensitivity curves which were straight, almost-horizontal lines for all films but type 649. The curve for the 649 film after the gamma component has been subtracted is illustrated in figure 7. Since the curve flattens at 2 lithium, we were able to obtain the thermal-neutron sensitivity only at 0 and 1 lithium. It was assumed that the sensitivity at 1 lithium was the more correct value.

The epicadmium-neutron flux affecting the films from 0 to 6 lithium was obtained by dividing the cadmium ratio into the thermal-neutron flux at each lithium thickness. By dividing the epicadmium flux by the epicadmium effect on the film, the epicadmium sensitivity of the films could be obtained.

V. RESULTS AND DISCUSSION OF RESULTS.

A. Thermal-Neutron Sensitivity.

A typical example of the curves obtained by the lithium-extrapolation method is illustrated for film type 606 in figures 8, 9, and 10.

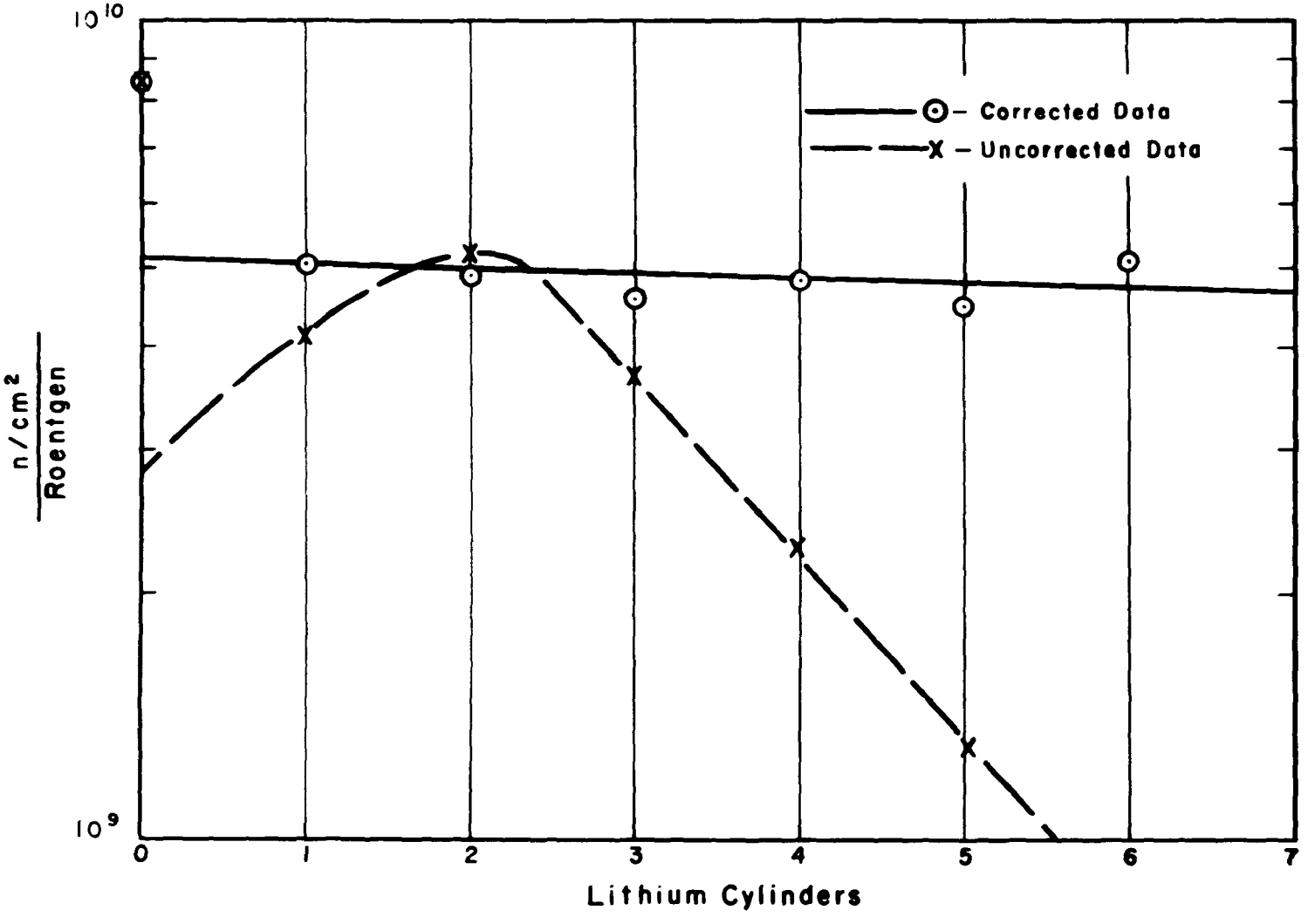

FIGURE 4

COMPARISON OF THERMAL-NEUTRON SENSITIVITY DATA WITH AND WITHOUT CORRECTION FOR EPICADMIUM NEUTRONS

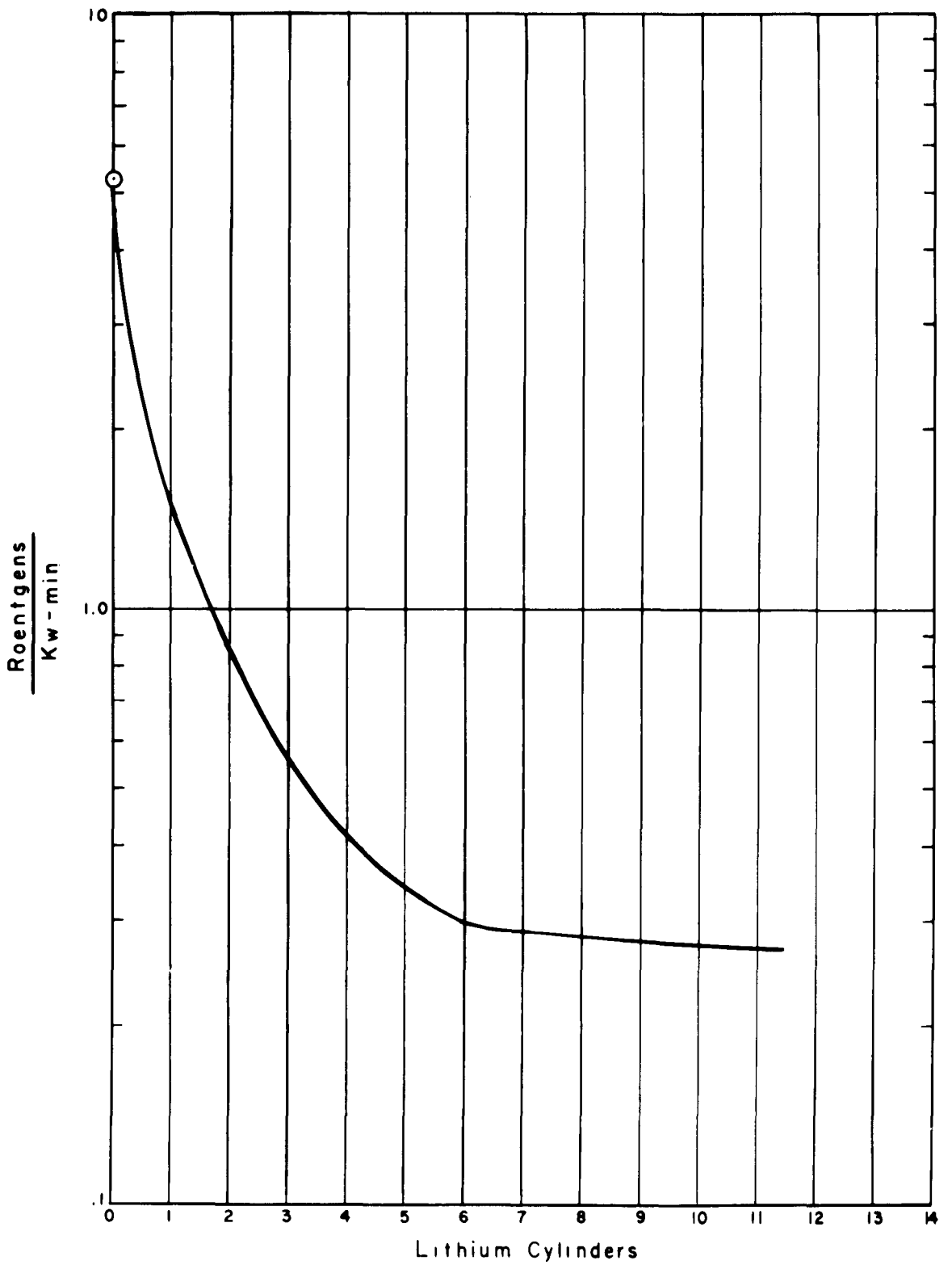

FIGURE 5

TYPICAL FILM RESPONSE CURVE WITH GAMMA COMPONENT SUBTRACTED

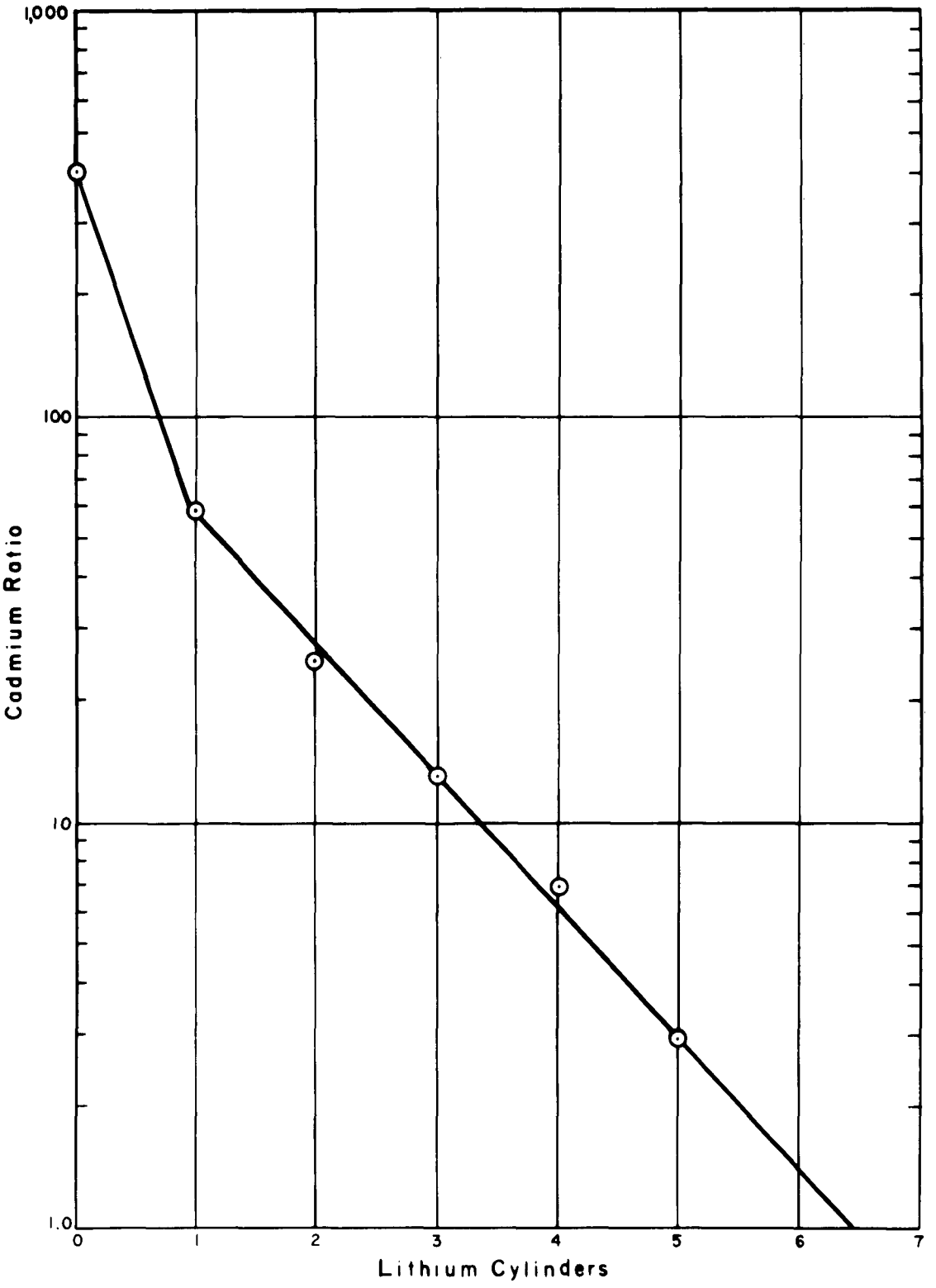

FIGURE 6

CADMIUM RATIO VERSUS LITHIUM CYLINDERS

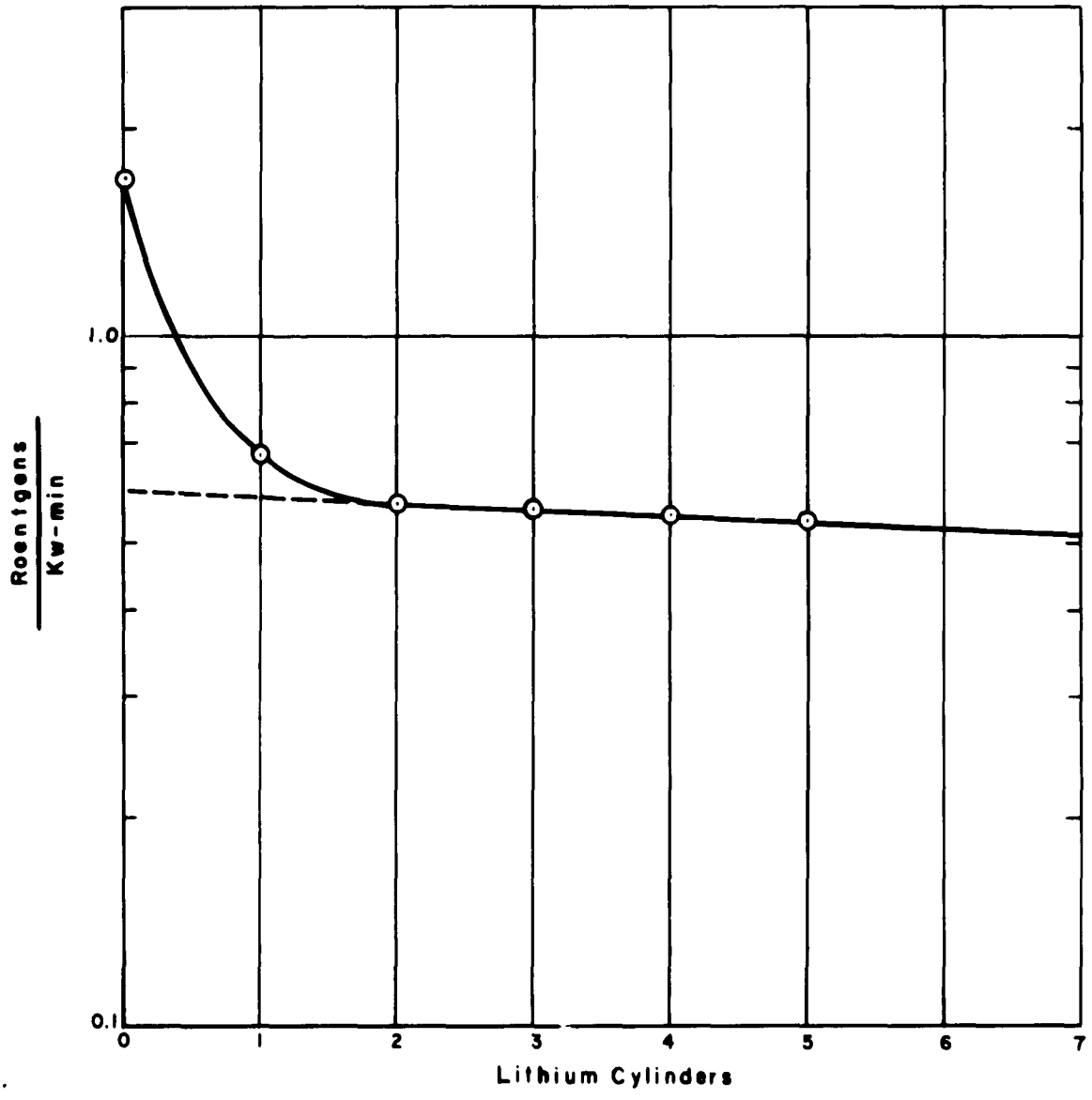

FIGURE 7

FILM TYPE 649 DATA AFTER SUBTRACTING GAMMA COMPONENT

The experimental film data curve, figure 8, was drawn as a best fit and the thermal-neutron-sensitivity curve, figure 10, was drawn by the method of least squares. Figure 9 shows a curve of the experimental film data minus the gamma component as well as an extrapolated curve. This extrapolated curve is due to epicadmium neutrons (neutrons whose energies are greater than the cadmium cutoff energy of 0.3 ev), and must be subtracted from the film data. This effect has been explained in section IV. C.

Table 2 shows the actual thermal-neutron sensitivities of each film type as compared with Ehrlich's results. Ehrlich irradiated the 510- and 606-film types at the Los Alamos Water Boiler Reactor and the 502-film type at ORNL.

The error in the thermal-neutron sensitivities of all the films but type 649 is estimated to be $\pm 25\%$ based on the propagation of the errors in the measurement of the thermal-neutron, gamma, and epicadmium fluxes as well as the inherent error due to the film itself. The error in the 649-film type is given as $\pm 50\%$ because the thermal-neutron sensitivity at only 1 lithium thickness could be obtained.

B. Epicadmium-Neutron Sensitivity.

An estimate of the epicadmium sensitivity of the films was obtained from the extrapolated curves as illustrated in figure 9. These results are presented in table 3.

The results indicate that the films are more sensitive to epicadmium neutrons than to thermal neutrons. These results seem logical since both silver and bromine have many resonance-energy absorption peaks in the energy range of 5 to 1000 ev. The cross sections for these absorption peaks are many times larger than the cross section for thermal neutron capture.

C. Fast-Neutron Sensitivity.

The fast-neutron sensitivities of the 508, 510, 1290, 502, 510, and 606 films are shown in figure 11. It must be noted that most of the points on the curves represent only one or two film irradiations. Thus, the statistics available for these results are almost nonexistent and no error can be quoted. These results should be used with extreme caution.

Ehrlich's results at 3 Mev are included in figure 11. Her data for the 502- and 606-film types fit our curves nicely, but her 510 data are about a factor of three lower than our data.

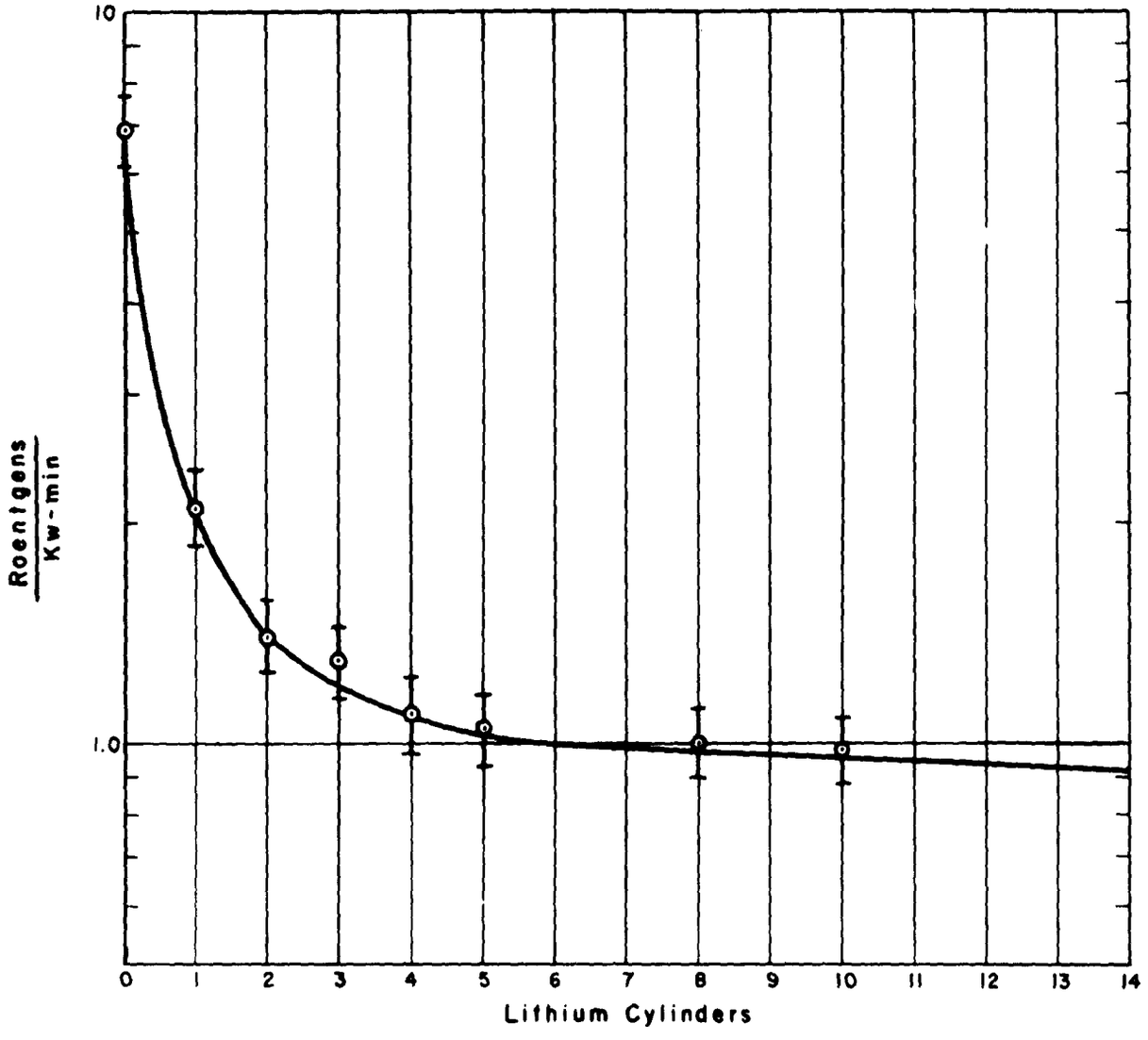

FIGURE 8

FILM TYPE 606 EXPERIMENTAL DATA

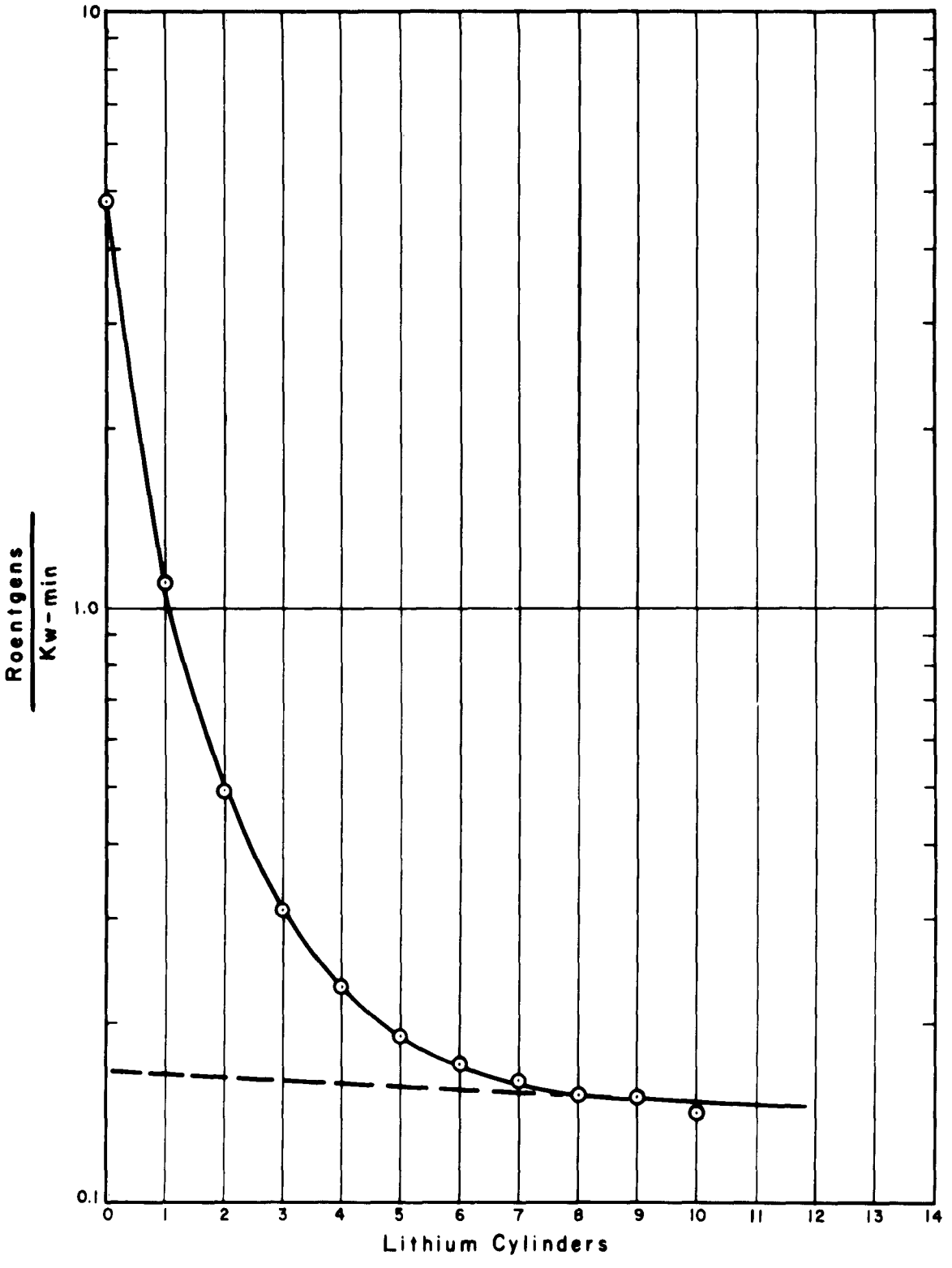

FIGURE 9

FILM TYPE 606 EXPERIMENTAL DATA MINUS GAMMA COMPONENT

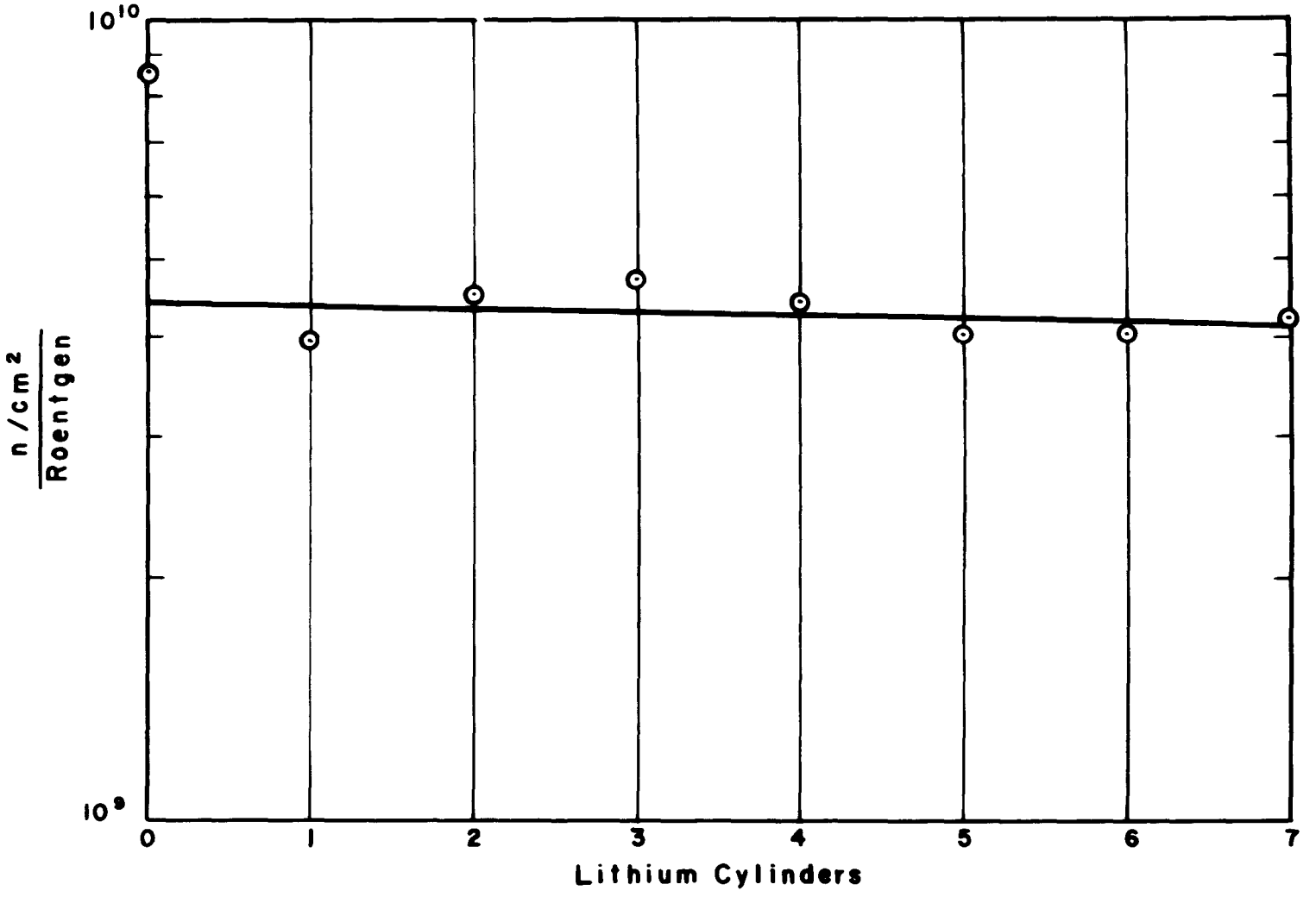

FIGURE 10

FILM TYPE 606 THERMAL-NEUTRON SENSITIVITY

TABLE 2

THERMAL-NEUTRON SENSITIVITY OF FILM

Film type	Thermal-neutron flux required to produce the same density as 1 r of Co^{60} radiation	
	NDL Results	Ehrlich results
	n/sq cm	
502	$4.0 \pm 1.0 \times 10^9$	5×10^9
510	$4.6 \pm 1.15 \times 10^9$	4.1×10^9
606	$4.4 \pm 1.1 \times 10^9$	3.7×10^9
508	$3.6 \pm 0.90 \times 10^9$	-
510	$4.8 \pm 1.2 \times 10^9$	-
1290	$4.9 \pm 1.2 \times 10^9$	-
548	$8.8 \pm 2.2 \times 10^9$	-
649	$4 \pm 2 \times 10^{10}$	-

TABLE 3

EPICADMIUM SENSITIVITY OF FILMS

Film type	Epicadmium flux required to produce the same density as 1 r of Co^{60} radiation
	n/sq cm
502	$9.2 \pm 2.3 \times 10^8$
510	$4.5 \pm 1.1 \times 10^8$
606	$5 \pm 1.3 \times 10^8$
508	$8.9 \pm 2.2 \times 10^8$
510	$5.4 \pm 1.4 \times 10^8$
1290	$5.8 \pm 1.5 \times 10^8$
548	$4.2 \pm 1.1 \times 10^8$
649	$1.5 \pm 0.5 \times 10^8$

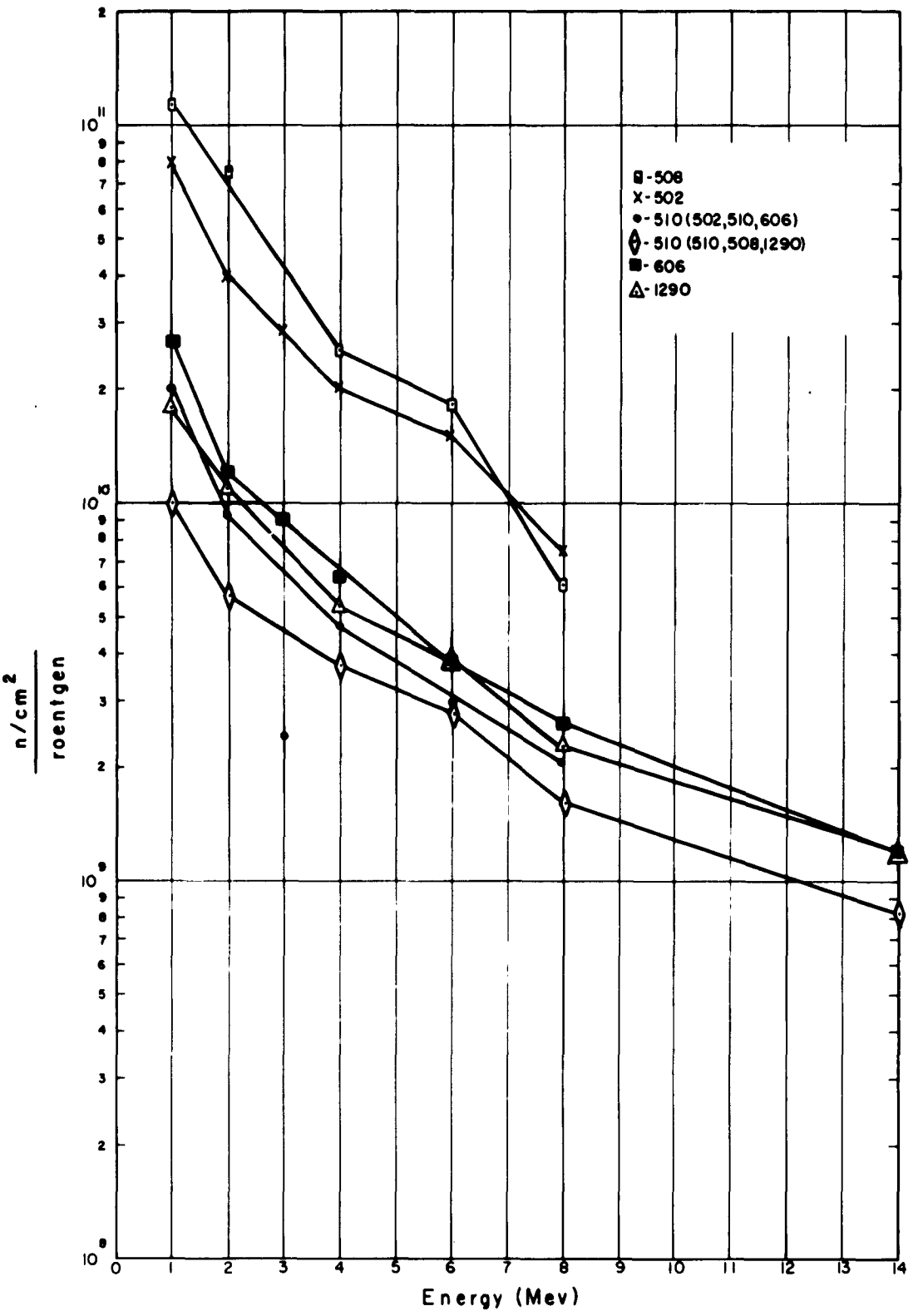

FIGURE 11

FAST-NEUTRON SENSITIVITY OF SIX FILMS

D. Neutron Sensitivity Based on Tissue Rads.

Recent results[10] indicate that the value of the energy loss, W, for electrons in air is closer to 35 ev than to the old value of 32.5 ev. If we use the value of 35 ev, the energy absorption in aqueous tissue for a dose of 1 r in the range of photon energies from 0.3 to 5 Mev will be nearly 100 ergs/g and will correspond almost exactly to 1 rad. Assuming that the NBS holder and the film are tissue equivalent materials, we can compare the neutron sensitivity of the films calculated on a rad to rad basis with gamma photons. The neutron rads were calculated by single collision theory. This comparison is illustrated in table 4. The table points up the great difference between the thermal-neutron sensitivity and the fast-neutron sensitivity of the films. The lower range films are approximately 10 times more sensitive to thermal neutrons than to Co^{60} gamma photons, whereas these same films are 5 to 270 times less sensitive to fast neutrons than to Co^{60} gamma photons.

E. Variation of Fast-Neutron Sensitivity With Grain Size.

Ehrlich[5] states that the ratio of the 3 Mev neutron-to-gamma ray sensitivities of the 502-, 510-, and 606-film types is roughly equal to the reciprocal of the ratio of their grain diameters. This ratio is 1:10:3 for 502-, 510- and 606-film types, respectively. Our fast-neutron sensitivities, shown in figure 11, confirm this observation; however, the ratio is different since the grain sizes we quote are different than Ehrlich's.

Table 5 compares the ratio of the reciprocal of the sensitivities of the various films with the ratio of the grain sizes. Since the grain sizes given in table 1 are quoted as limits of or average grain sizes, table 5 quotes the grain size ratio in terms of average. Using the average values for both ratios of the reciprocal of fast-neutron sensitivities and grain sizes, it is obvious that the two ratios are very close. The ratios are 1:1.4:5.0:6.8 and 1:1.4:3.6:6.4 for the reciprocal of the fast-neutron sensitivities and the grain sizes, respectively. The values for the two 510 types are averaged together as are the 1290 and 606 types since the average grain sizes for each group are the same.

The most glaring difference is between the 510-film types, which are identical films but are used in a different film packet. The different film packets containing the 510 films, however, were not manufactured at the same time. In fact the 502-, 510-, 606-film packet is 2 years older than the 508, 510, 1290 packet. It is possible that the manufacturing process may have been altered during this period and that aging may have affected the films.

TABLE 4

NEUTRON SENSITIVITY OF FILM IN TERMS OF TISSUE RADS

Neutron energy Mev	Number of neutron rads required to produce the same density as 1 rad of Co^{60} radiation							
	Film type							
	502	510	606	508	510	1290	548	649
Thermal	0.11	0.12	0.12	0.097	0.13	0.13	0.24	1.1
1	223	45	60	268	22	40		
2	123	20	37	230	18	34		
3	100	9	32					
4	82	19	27	103	15	22		
6	70	14	18	84	13	18		
8	38	11	13	31	8	12		
14			7		5	7		

TABLE 5

COMPARISON OF THE RATIO OF THE RECIPROCAL OF THE FAST-NEUTRON SENSITIVITIES WITH THE RATIO OF THE GRAIN SIZES

Energy Mev	Film types					
	510 (508,1290)	510 (502,606)	1290	606	502	508
1	1.0	2.0	1.8	2.7	8.0	11
2	1.0	1.6	1.9	2.1	7.0	13
4	1.0	1.3	1.4	1.7	5.4	6.8
6	1.0	1.1	1.4	1.4	5.4	6.4
8	1.0	1.3	1.4	1.6	4.6	3.8
14	1.0	-	1.5	1.5	-	-
All	1.0		1.4		5.0	6.8
Grain size average	1.0	1.0	1.4	1.4	3.6	6.4

No fast-neutron-sensitivity work was done with the very high-range films 548-0 and 649. It would seem that based on grain size ratios, the 649-film type should be 10 times more sensitive to fast neutrons than the 510-film types.

Since much of the data presented concerning fast neutrons and film is based upon one or two film irradiations at each energy, the reader is again cautioned to use the results with care.

Correction factors for the effects of capture gamma from soil and blast shields on film are being evaluated and will be reported in subsequent papers.

VI. CONCLUSIONS.

The thermal-neutron and fast-neutron sensitivities of the eight films that have been determined by this experiment can be utilized to correct film data obtained at nuclear weapons tests.

Further experimental work with fast neutrons is needed to increase the statistical accuracy of our results as well as to obtain fast-neutron sensitivities of the very high-range films, 548 and 649. Two points seem evident concerning the fast-neutron sensitivity of film. They are: (1) the sensitivity of the films increases with increasing neutron energy from 1 to 14 Mev, and (2) the ratio of the sensitivities of the films is roughly equal to the reciprocal of the ratio of their grain sizes.

In order to obtain meaningful data from neutron experiments conducted in a reactor thermal column, corrections must be made for the neutron sink effect of the object being irradiated. The lithium-extrapolation method for obtaining these correction factors has been refined and revised so that the method may be used with confidence.

LITERATURE CITED

3. Tochilin, E., Shumway, B. W., and Kohler, G. D. Rad. Res. 4. 467 (1956).

4. Mercer, T. T., and Golden, R. USNRDL-TR-493. Response of Photographic Emulsions to Thermal and Epithermal Neutrons. December 1960. UNCLASSIFIED Report.

5. Ehrlich, M. Health Physics 4. No. 2, 113 (1960).

6. Ehrlich, M. Photographic Dosimetry of X and Gamma Rays. NBS Handbook 57. August 1954.

7. Sayeg, J. A., and Harris, P. S. AEC-LA-2174. Experimental Determination of Fast and Thermal Neutron Tissue Dose. May 1958. UNCLASSIFIED Report.

8. Graves, G. A., and Roach, W. H. LA-1964. Some Foil Absorption Calculations. (1955). UNCLASSIFIED Report

9. Brennan, J. T., Harris, P. S., Carter, R. E., and Langham, W. H. LA-1408. The Biological Effectiveness of Thermal Neutrons on Mice. (1952). UNCLASSIFIED Report.

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THERMAL AND FAST NEUTRON EFFECTS ON DOSIMETER FILMS
Robert J. Smith

NDL-TR-13, October 1961
Army Task No. 4N12-10-007-04, UNCLASSIFIED REPORT

In order to accurately measure the initial gamma radiation from atomic detonations, the effect of neutrons on gamma detectors was evaluated. Eight film types, encased in NBS holders and covering a range of 0.3 to 50,000 r, were exposed to thermal-and fast-neutron radiation. The lithium extrapolation method was used in the evaluation. Two points seem evident concerning the fast-neutron sensitivity of film: (1) the sensitivity of the film increases with increasing neutron energy from 1 to 14 Mev and (2) the ratio of the sensitivity of the film is roughly equal to the reciprocal of the ratio of their grain sizes.

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3. Neutrons, thermal effect on dosimeter films flux sensitivity interaction with film
4. Neutrons, fast Effect on dosimeter films sensitivity interaction with film
5. Neutron, thermal lithium extrapolation technique

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Nuclear Chemistry Division, U. S. Army Nuclear Defense Laboratory, Army Chemical Center, Maryland

THERMAL AND FAST NEUTRON EFFECTS ON DOSIMETER FILMS
Robert J. Smith

NDL-TR-13, October 1961
Army Task No. 4N12-10-007-04, UNCLASSIFIED REPORT

In order to accurately measure the initial gamma radiation from atomic detonations, the effect of neutrons on gamma detectors was evaluated. Eight film types, encased in NBS holders and covering a range of 0.3 to 50,000 r, were exposed to thermal- and fast-neutron radiation. The lithium extrapolation method was used in the evaluation. Two points seem evident concerning the fast-neutron sensitivity of film: (1) the sensitivity of the film increases with increasing neutron energy from 1 to 14 Mev and (2) the ratio of the sensitivity of the film is roughly equal to the reciprocal of the ratio of their grain sizes.

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3. Neutrons, thermal effect on dosimeter films flux sensitivity interaction with film
4. Neutrons, fast Effect on dosimeter films sensitivity interaction with film
5. Neutron, thermal lithium extrapolation technique

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